Evidence for Microscopic Diffusion Anisotropy in Spinal Cord Tissue Observed with DWV Imaging on a Whole-Body MR System

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Double-wave-vector diffusion-weighting (DWV) experiments [1] can be used to characterize local spin diffusion in tissue. They have been successfully applied to detect restricted diffusion [2] and diffusion anisotropy present on a microscopic level in macroscopically isotropic samples [3]. Thereby, the additional degree of freedom, the angle between the two wave vectors, is explored by rotating the direction of the diffusion-weighting gradients of the two periods relative to each other. However, the experimental demonstration of the anisotropy effect that yields a reduced signal for orthogonal wave vectors compared to parallel or antiparallel wave vectors, has been limited to high-field NMR spectrometers with maximum gradient amplitudes of 300mT/m and above [3,4]. In this work, evidence for the detection of the anisotropy effect on a standard whole-body MR system (maximum gradient amplitude 40mT/m) is provided.

Methods

Experiments were performed on a 3T whole-body MR system (Siemens Magnetom Trio) using a circularly polarized transceive wrist coil. Images of a formalin-fixed pig spinal cord phantom and a n-Dodecan ($C_{12}H_{26}$) phantom as a reference were acquired. DWV measurements were based on echo-planar imaging with a single refocusing RF pulse and an in-plane resolution of 1.0 x 1.0 mm^2 at a slice thickness of 10 mm (TE/TR = 185 ms / 6 s). Two diffusion-weighting periods were applied with a b-value of 1000 s/mm^2 each, a diffusion time Δ of 72 ms, and a mixing time τ_m of 28 ms. Two different directions schemes were used for the diffusion weighting: (i) the 64 orientation combinations obtained from eight directions uniformly distributed in the image plane (10 averages) and (ii) the anisotropy direction scheme covering 15 wave vector orientation combinations that can be used to estimate the microscopic anisotropy [5] (15 averages). The on-resonance signal contributions of the formalin were nulled by an inversion recovery pulse preceding the initial excitation by about 1s to minimize ringing effects, off-resonance contributions, e.g. due to the methanol portion of the formalin, were suppressed with a chemical-shift-selective saturation pulse prior to the initial RF excitation.

To minimize the impact of concomitant effects like background gradient fields or macroscopic diffusion anisotropy all images sharing the same angle between the two wave vectors were averaged for the experiments covering 64 direction combinations. To check the expected anisotropy effect, images with orthogonal wave vector orientations were subtracted from the averaged images obtained with parallel and antiparallel orientations. The latter was performed to correct for the potential influence of the restriction effect that shows a cosine-shaped signal modulation and would introduce a difference between parallel and antiparallel orientations but also between parallel and orthogonal orientations. For the measurements using the anisotropy direction scheme, the signals were fitted to the tensor equation given in [5] and the rotationally invariant anisotropy calculated.
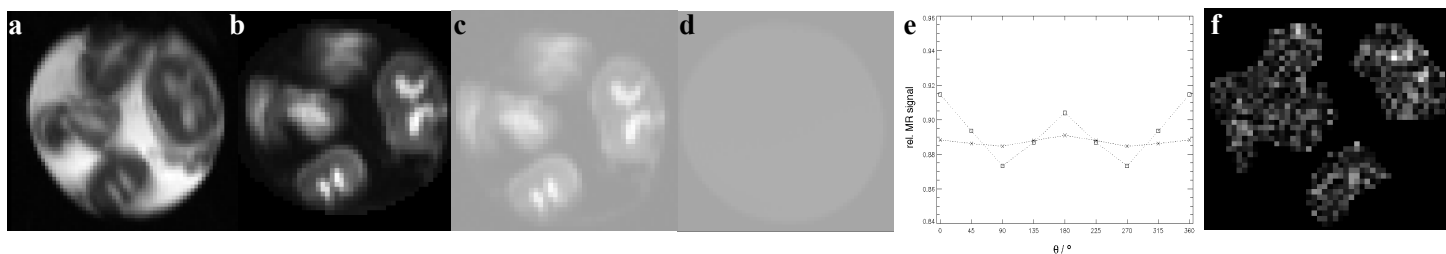

Figure 1: Images of the spinal cord phantom acquired (a) without inversion recovery and (b) with diffusion weighting. (c,d) Difference image of parallel/antiparallel and orthogonal wave vector orientations for (c) the spinal cord phantom and (d) the dodecane phantom. (e) Signal modulations vs. the angle θ between the two wave vectors observed in the spinal cord phantom (squares) and the dodecane phantom (x). Note that the curves are symmetric because images that share the same angle between the two wave vectors are averaged, i.e. the data points at θ and θ+180° are identical. (f) map of the microscopic anisotropy measure *MA*.

Results and Discussion

The results are summarized in Fig. 1a to 1f. A signal modulation consistent with the expected cos 2θ dependency is observed in the pig spinal cord with an amplitude of about 4%. A similar modulation appears in the dodecane phantom but is with an amplitude of below 0.5% considerably lower. Thus, although some systematic signal modulation may be present, it is very likely that most of the modulation observed within the spinal cord reflects the anisotropy effect of DWV experiments at long mixing times. The map of the microscopic anisotropy measure shows some increased values within the spinal cord, however, additional averaging may be required for a more reliable result.

In conclusion, evidence for the detection of microscopic anisotropy with DWV experiments on a whole-body MR system is provided.

References

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